OSCILLATIONS IN GAS-TURBINE COMBUSTORS; CONTROL OF RUMBLE, PATTERN FACTOR AND EMISSIONS

Final Technical Report

by

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INTRODUCTION

The proposal which led to the above contract required that measurements be obtained in the combustor of a small gas turbine so as to determine the extent to which oscillations of the gaseous fuel supply would lead to reductions in NOx emissions and improvements in pattern factor.

The 60 degree sector of the annular combustor in which the measurements were obtained is shown on figure 1 and has been used for many previous steady-state experiments, see for example Bicen, Senda and Whitelaw (1988). It operated with a single primary-zone vortex driven by three film-cooling wall jets and curtailed by the five primary jets. Dilution was achieved with four jets from the outer diameter and two from the inner diameter and directly opposite to two of the outer jets. Results were obtained with and without a turn-around duct, as used in the helicopter for which the engine was designed. The air was supplied through a plenum chamber surrounding the main combustor and a second plenum surrounding the turn-around duct with its own film cooling.

The combustor was operated with methane fuel and earlier experiments with kerosene, supplied to an atomiser and then to a T-vaporiser as described by Liu, Perez-Ortiz and Whitelaw (1992), were followed here with the gaseous fuel supplied through two cones, each in line with the centres of the legs of the T-vaporiser which they replaced, and each with 10 mm diameter holes normal to each of the 45 degree cones. The liquid flow to the T-vaporiser was pumped under constant pressure or by means of one of the unsteady injectors referred to above and mixed with air prior to entering the vaporiser. The air was preheated electrically to 150 and 250 ^{o}C and the air-fuel ratio was varied to give overall equivalence ratios of 0.21 and 0.35. With the gaseous fuel, the simple vane device described by Sivasegaram, Tsai and Whitelaw

(1995) was used to oscillate the flow of air and fuel, again with overall equivalence ratios of 0.21 and 0.35, so that the rise in temperature within the combustor was close to that with kerosene as fuel.

Flow rates, noise characteristics, temperature and concentrations of major species and on NOx were measured in all experiments. Calibrated rotameters provided the flow rates so that uncertainties in the determination of heat-release rates and of air-fuel and equivalence ratios were within 2% and had no effect on the conclusions. Wall and sound pressures were measured with the pressure transducer and a free-field microphone, respectively, with frequency analysis where required (Spectral Dynamics 340); amplitudes were determined within 0.01 kPa and frequencies within 1.25 Hz.

Digitally compensated thermocouples were used to measure temperature characteristics and made use of 50 μm diameter Pt/13% Rh-Pt wires mounted on 300μm wires of the same material. Gas samples were obtained from a water-cooled probe of 0.5 and 6 mm inside and outside diameters. NOx and unburned hydrocarbons were determined on a wet basis by chemi-luminescence and flame ionisation detectors (Thermo-Environmental Instruments 42 and Analysis Automation 520); and carbon monoxide and carbon dioxide on a dry basis by infra-red detectors (Analysis Development Co. 483-4027 and 483-4026).

RESULTS

The results presented here are a small and representative sample of the total. They are presented first for gas combustion, as required by the Contract, and then for kerosene combustion so as to present as complete a picture as is possible; in the latter case, the results include those of Perez-Ortiz (1996) which were obtained in the same combustor with some small geometric differences. In both cases, the fuel supply was subjected to oscillations at frequencies in a range from around 75 to 200 Hz with the present results confined to the range from 100 to 150 Hz since lower frequencies gave rise to unacceptably rough combustion and higher frequencies appeared to offer no advantages. Also, the short length of the combustor implied that there were no recognisable acoustic frequencies although there was a tendency for oscillations imposed at 100 Hz to be amplified.

Oscillation of the flow of natural-gas fuel led to increases in the free-field noise levels as large as 6 dB, measured orthogonal to the combustor and 1 m from the exit of the curtailed combustor section. This increase in noise led to an increase in the spatially-averaged rms of temperature fluctuations in the exit plane. In the absence of combustion, the turbulence intensity was approximately 10 % with no imposed oscillations and 17 % when the flow of fuel was oscillated at a frequency of 100 Hz. This increase in rms levels can be expected to improve mixing and, therefore, the temperature distribution at the exit.

Concentrations of NOx were measured at each of 48 locations as a function of amplitude and frequency, and this procedure helped to provide meaningful comparisons when the concentrations were low. With overall air-fuel ratios of 70 and 42, the imposed sinusoidal oscillations led to reductions in the average exit-plane

NOx concentrations of 17 and 8 %, that is from 13.2 to 11.2 ppm and 34.4 to 32 ppm, respectively, and were more pronounced in regions of highest temperature. The reduction in NOx due to the oscillation of fuel was due to the oscillation of fuel concentration leading to burning on either side of stoichiometry with the different air-fuel ratios associated with different ranges of equivalence ratio and differences in the reduction of NOx emissions. The combustion efficiency was unaltered by the imposed oscillations with negligible changes in the exit plane concentrations of unburned hydrocarbon and carbon monoxide. Measurements with lower amplitudes of imposed oscillation showed that the decrease in NOx concentrations was not linear and frequencies between 100 and 150 Hz had no effect on the extent of the reduction.

An alternative to the approach of the previous paragraph is to oscillate the two fuelling devices with the same frequency and phases which are different by 180 degrees. Thus the near field of each fuelling device will be subject to periodic variations and, since this is the region where we can expect much of the combustion, the generation of NOx may be reduced. But the periodicity of the two fuelling devices will tend to cancel each other so that the downstream region may be free of the pressure waves which gave rise to the increase in free-field noise of the previous paragraphs. Figure 2 allows comparison of distributions of the concentration of NOx in the exit plane of the combustor with the two fuelling devices operated with constant flow and then driven with the same amplitude and a frequency of 100 Hz and with the same phase and 180 degrees out of phase. The distributions with the imposed oscillations are similar with the 17 % reduction in the averaged concentration of referred to above. The pressure amplitude with the out-of-phase oscillations was nearly identical to that without imposed oscillations so that the free-field noise level without oscillations was *94.5* dB compared to values of *98.5* and *95* dB with in- and out-of-phase oscillations. Consistent with this result and with the absence of a pressure wave with out-of-phase oscillations, the pattern factor was not modified .

Kerosene fuel was injected through the T-vaporiser with the aid of an automobile-type injector, mixed with atomising air and emerged from the two legs of the T-vaporiser to impinge on the head of the combustor with consequently good mixing and low pattern factors. The air supplied with the injected fuel was preheated and results were obtained with two values of preheat and air-fuel ratio corresponding to the values of cruise and take off. The performance of the vaporiser was consistent over long periods but did vary as carbon built up on the inside surfaces. Thus, initial tests led to free-field sound intensities which were increased by 6 dB by the oscillations and later tests led to lower values. Some changes in the performance of the combustor were also experienced as the annular gaps of the film-cooling rings changed with time. The first results, figure 3, corresponded to an increase in free-field sound intensity from 97 to 103 dB and to reductions in averaged NOx concentration from 22 to 12 ppm with a small deterioration in combustion efficiency as shown by the contours of concentration of unburned hydrocarbon. The total quantity of unburned hydrocarbon would have had negligible effect on the NOx concentrations with the higher air-fuel ratio and could have been responsible for not more than 1 ppm with the lower air-fuel ratio.

In later tests, the imposed oscillations corresponded to an increase in free-field sound from 96 dB to 100 dB and the maximum reduction in average NOx concentrations was around 15 %, from 24.7 to 20.4 ppm with preheat temperature and air-fuel ratio similar to those of take off condition, see figure 4.

The corresponding increase in rms levels led to the improved pattern factors of figure 5, depending on the amplitude of oscillations. At the smallest preheat temperature, a moderate increase in noise was sufficient to improve the pattern factor because more time was available for mixing than at higher preheat temperatures where a small increase in noise sometimes led to the deterioration of the pattern factor.

DISCUSSION

The reductions in NOx concentrations which stem from oscillations are likely to be associated with the superposition of the corresponding discrete-frequency oscillation on the more random turbulent spectrum of the various flows. Since the maximum temperature at any location and time is limited to that of the adiabatic flame, the near-sinusoidal oscillation will tend to lower the mean and to reduce the time spent at the highest temperatures. Thus the imposed frequency implies that the corresponding probability density distribution will approximate to two delta functions and separation larger than that of the half width of a near Gaussian distribution so that the mean is reduced and thermal NOx generated in smaller quantities. These suppositions require confirmation from measurements of temperature probability density functions, preferably in simpler flows.

The extent of the reduction of NOx in each of the above flow arrangements depended on the flow boundary conditions and the way in which oscillations altered the spatial and temporal distribution of fuel concentration and, therefore, temperature in the region of active burning. The importance of the amplitude of oscillations to NOx concentrations was consistent for the flow arrangements and is confirmed by the absence of a significant reduction in NOx in the experiments of Keller, Bramlette, Barr and Alvarez (1994) with a premixed pulse combustor, where they attempted to reduce NOx by using oscillations of small amplitude associated with vortex shedding to alter the residence time at the highest temperature.

Nina, Pita, Gonçalves and Gutmark (1996) controlled naturally occurring oscillations in a partly premixed flame behind a bluff-body by the oscillation of fuel and observed a decrease in NOx concentration with amplitude of oscillation. The correlation between NOx concentration and amplitude was, however, less clear than in the present experiments. Sivasegaram and Whitelaw (1996) oscillated the flow of fuel in a burner arrangement typical of those used in furnaces, with the phase difference between the sinusoidal input to the loudspeaker and the pulsed injection of around 5 % of the gaseous fuel behind the disk as variable, and found that the NOx concentration always decreased with amplitude of oscillation. The weaker correlation between amplitude and NOx concentration in the study of Nina et al appears to be due to the complex effect of combustion oscillations on the spatial and temporal distribution of fuel.

In general, the results show that NOx concentrations can be reduced by useful amounts but at the cost of pressure fluctuations which may be unacceptable in practice, except in devices where such oscillations already exist and can be taken advantage of, for example, the suggested use of a Rijke tube to burn coal with reduced NOx emissions (Zinn, 1992). On the other hand, it is evident that this penalty may not have to be paid where it is possible to oscillate two neighbouring flows at the same frequency and opposite phase. The control of naturally occurring oscillations in practical combustors could imply an inevitable increase in NOx concentration which could be averted by the partial reduction of noise since NOx concentrations do not increase linearly with amplitude. It is possible, on the other hand, to achieve a reduction in NOx as well as in noise, by active control with the amount and duration of injection of secondary fuel arranged so that combustion occurs on either side of stoichiometry.

The reduction of pattern factor by increasing combustion noise may not be a real benefit and small amplitudes of oscillation of fuel can have detrimental effects on combustion noise as well as the pattern factor. Experiments with oscillation of fuel in opposite phase have shown that it was possible to achieve a reduction in NOx concentration without affecting the pattern factor, and it should be possible to modify independently the spatial and temporal distributions of fuel so that reductions are attainable in both NOx and pattern factor.

CONCLUDING REMARKS

The oscillation of fuel in the 60 degree sector of a gas turbine combustor led to a reduction in NOx concentration which depended on the amplitude of the oscillated input. Reductions of around 40 % were accompanied by a 6 dB increase in combustor noise with kerosene as fuel. A reduction of 17 % was attainable with gaseous fuel and a similar increase in noise, and it has been shown that this reduction was attainable without the penalty of noise by opposed-phase oscillation of fuel in adjoining fuel inlets.

The oscillation of fuel with a 6 dB increase in noise level also led to a more even distribution of the exit plane temperature, with reductions of up to 20 % in the pattern factor. Smaller amplitudes of oscillation of fuel did not have a beneficial effect on the pattern factor.

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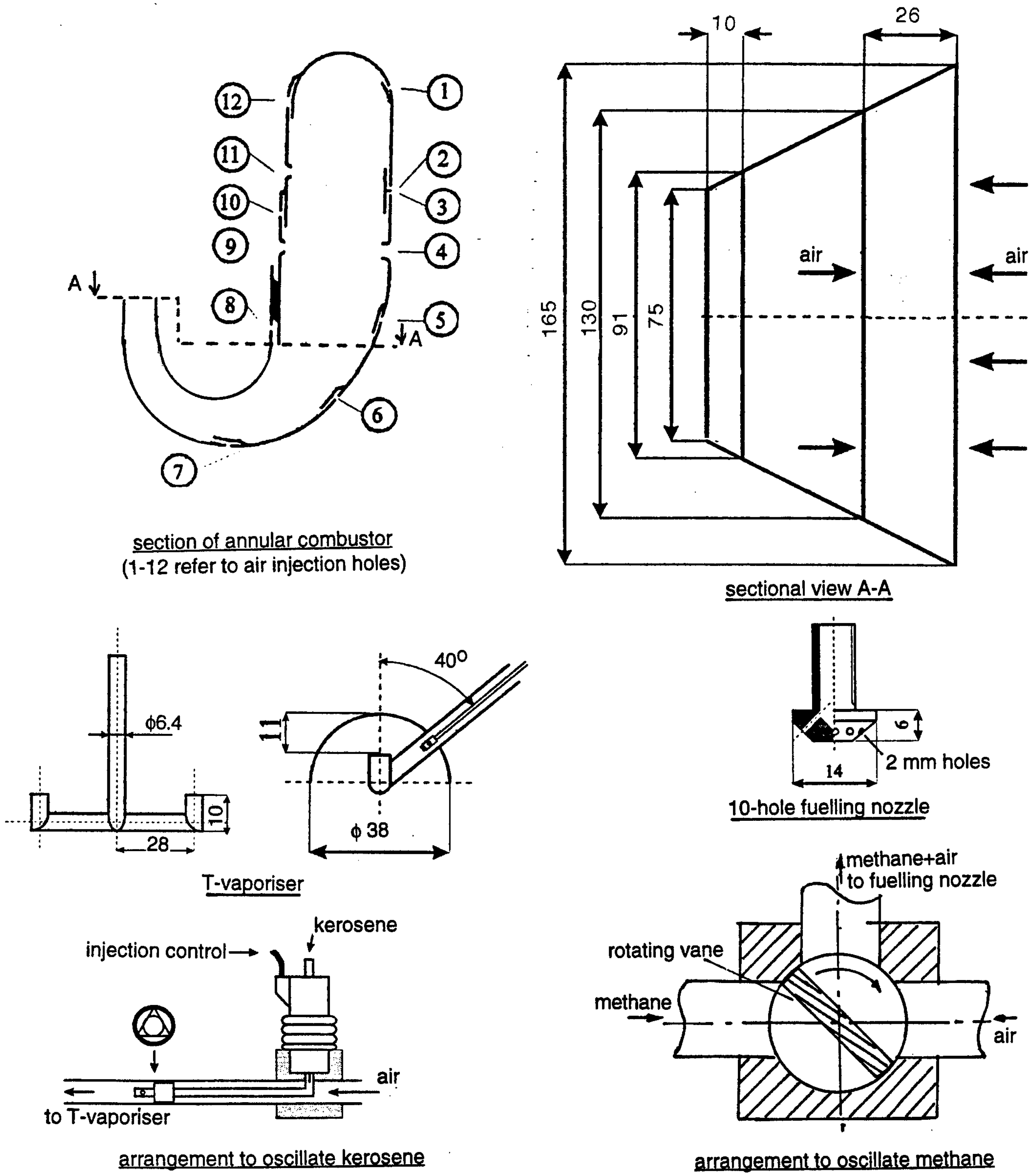

Figure 1: Sector of annular gas turbine combustor

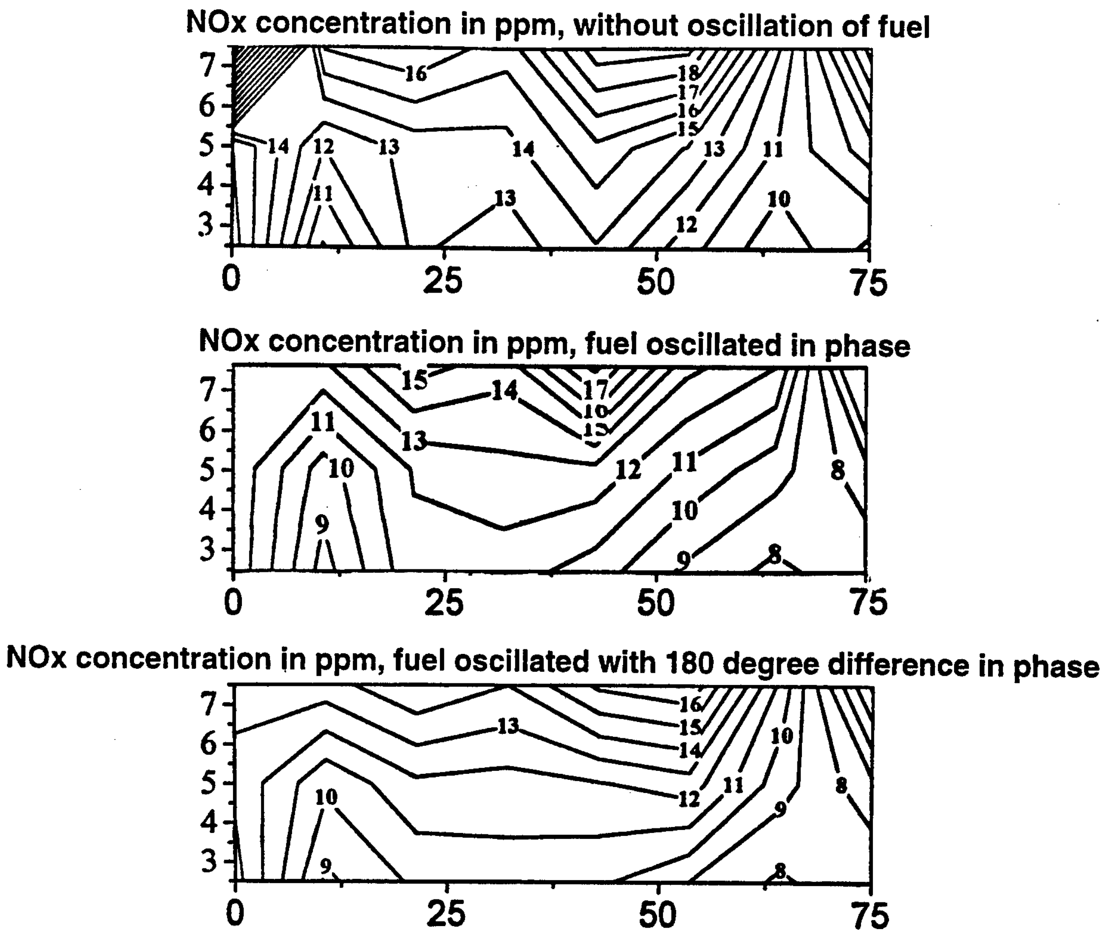

Figure 2: Exit profiles of NOx concentration without and with oscillation of gas fuel with turnaround duct, air preheated to 150°C, $\phi = 0.21$, heat release = 25 kW, fuel oscillated at 100 Hz (Spatial mean NOx concentration without oscillation of fuel =13.2 ppm; with fuel oscillated in phase =11.2 ppm; fuel oscillated with 180 degree difference in phase =11.2 ppm)

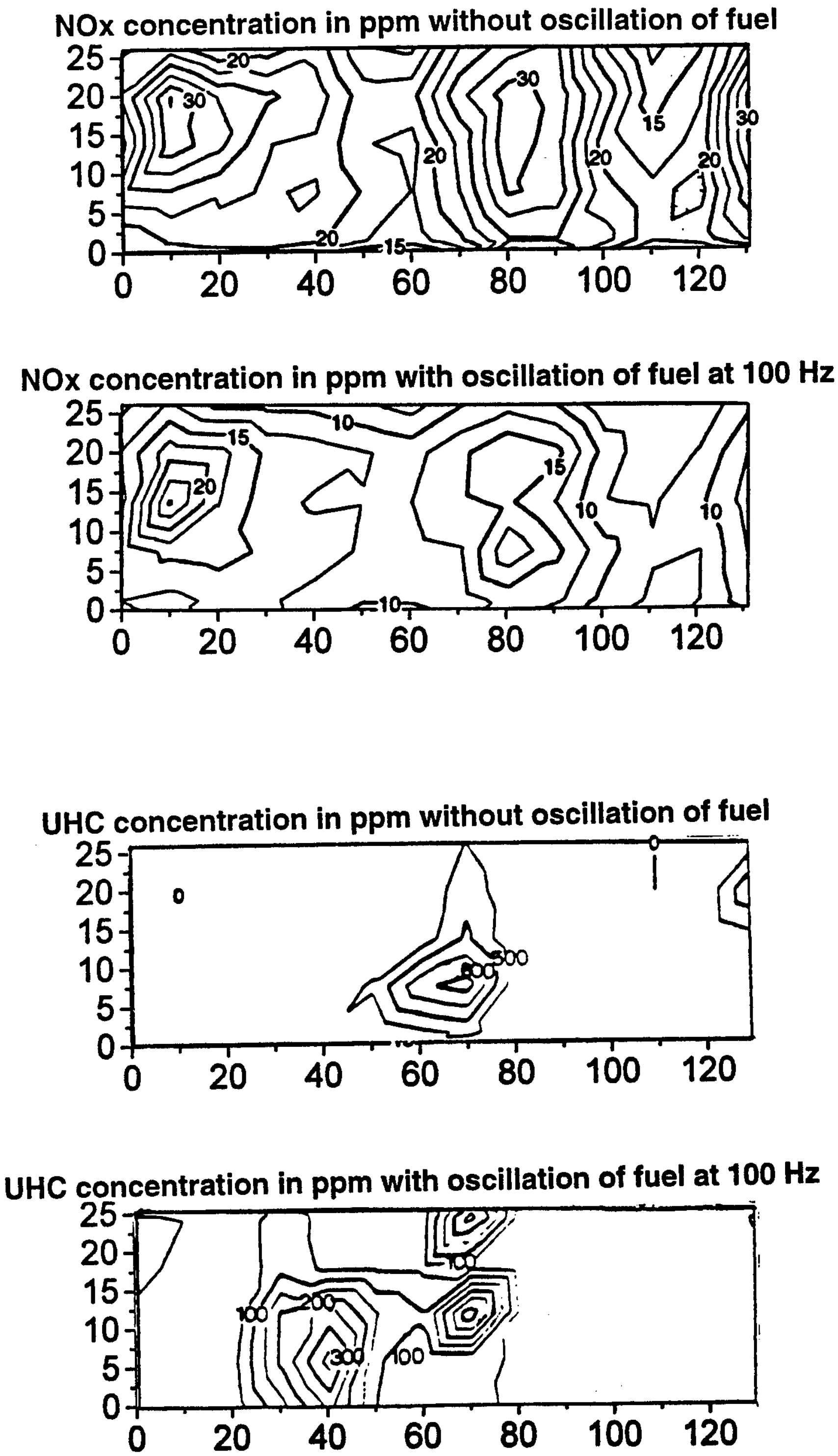

Figure 3: Exit profiles of NOx and unburned hydrocarbon concentrations without and with oscillation of liquid fuel

without turnaround duct, air preheated to 150°C, ϕ = 0.35, heat release = 42 kW

(Spatial mean NOx concentration without oscillation=22ppm, with oscillations=12ppm; spatial mean concentration of UHC without oscillation=60ppm, with oscillation=90ppm).

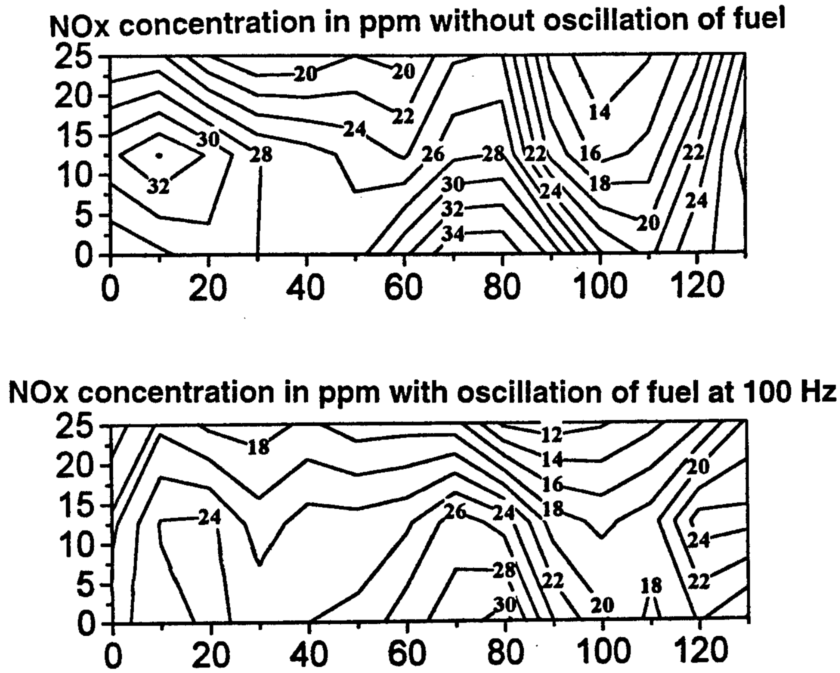

Figure 4: Exit profiles of NOx concentration without and with oscillation of liquid fuel without turnaround duct, air preheated to 250°C, $\phi = 0.21$, heat release = 25 kW (Spatial mean NOx concentration without oscillation = 24.7ppm, with oscillations = 20.4ppm. Spatial mean UHC concentration without oscillation = 5 ppm, with oscillations = 300 ppm).

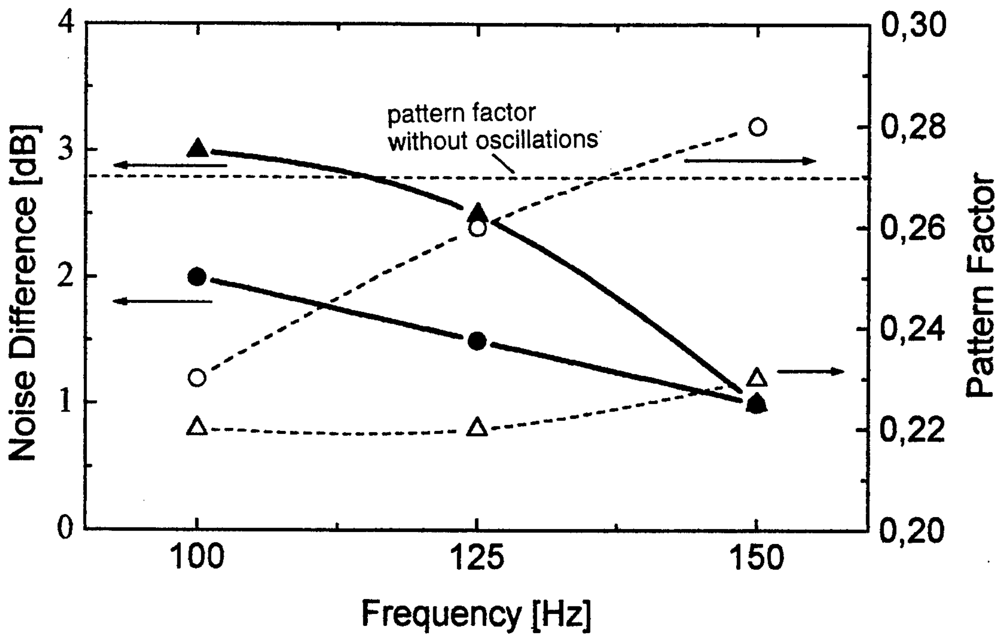

Figure 5: Influence of increase in combustion noise on pattern factor
with turnaround duct, liquid fuel, heat release = 25 kW
●, ○, $\phi = 0.21$, air preheated to 150°C; ▲, Δ $\phi = 0.35$, air preheated to 250°C